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LUNAR OPTICAL TELESCOPES: AN HISTORICAL PERSPECTIVE

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Abstract

There is a long history of thought and discussion on the possibilities of astronomical observatories on the Moon. Numerous ideas have been suggested and a variety of concepts have resulted for lunar optical telescopes. This paper reviews some of the ideas and efforts of individuals and working groups including Hershel, Clarke, Malina, Herbig, and Hess; working groups of the 1960s; and recent initiatives of Burke, Burns, and others. The enhanced technologies of the 1980s and 1990s can make past dreams of lunar observatories come to reality in the 21st century.

The Expectation

That an astronomical observatory on the Moon offers the potential advantages of emplacement on a stable platform in an environment unencumbered by atmospheric obscurations has long been recognized. The National Academy of Sciences report, Astronomy and Astrophysics for the 1980s, listed seven promising programs for the 1990s and beyond. All of these programs involved space-based observations and one of the programs was entitled Astronomical Observations on the Moon.

The report states:

> The Moon offers certain decisive advantages as a base for astronomical observations. In particular the far side of the Moon provides protection from the radio interference from sources on or near Earth and therefore has great potential for radio astronomy. Shielded at all times from earthlight, sites on the far side of the Moon are also shielded from sunlight for substantial portions of each month and thus offer advantages for optical and infrared observations requiring the darkest possible sky.

The report then adds that sites on the Moon must be preserved for astronomical observations and that international planning efforts should commence for establishment of lunar observations early in the next century (Astronomy and Astrophysics for the 1980s, 1982). This paper reviews some of the history of thought relating to astronomical observatories on the Moon that has led to these conclusions regarding the advantages of the lunar surface as an observatory site.

Highlights of Past Efforts

In a recent paper, Johnson and Leonard (1985) noted that the idea of a telescope in space was mentioned in 1923 when H. Oberth, a German rocket pioneer, suggested an orbital telescope. Oberth realized the advantage of observations in space where stars do not twinkle and where there is negligible absorption in the ultraviolet and infrared (Longair and Warner 1979). Since the launch of Sputnik in 1957, many significant contributions to astronomy have been made by OAO, SAS-I (Uhuru), Ariel, ANS, Copernicus Orbiting Observatory, Skylab, OSO-7, Solar Max, Explorer, IMP and others. The Infrared Astronomy Satellite (IRAS) was a success in opening new windows to understanding the solar system and the universe. The Einstein Observatory (HEAO–2) in 1979 probed X ray sources. The Hubble Space Telescope (HST) was launched in 1990 followed by the Gamma Ray Observatory in 1991. Further in the future are the Space Infrared Facility and the Advanced X ray Astronomy Facility. The great space observatories are complementary in that they span a range of wavelengths and each of these instruments is built upon earlier successful orbiting observatories. As the generations of orbiting observatories have complemented Earth-based astronomy, the Moon-based telescopes of the future can complement terrestrial and orbital instruments.

Establishment of scientific requirements and development of conceptual designs for any space-based telescope is a lengthy and iterative process. The HST was first proposed in the early 1960s at the summer study (Longair and Warner 1979). Meetings in 1967 and 1968 by an NAS ad hoc committee discussed how a space telescope could be used. A 1974 AIAA Symposium led to additional discussion of space telescope use. The NASA Space Telescope project was initiated by an advanced study (Phase A) activity in 1971 and 1972. During 1973-1976, Phase B scientific definition studies were carried out. Final design and development (Phases C and D) began in 1977, the year that Congress approved a 2.4-m space telescope. Launch of this HST is anticipated in late 1989. The telescope is to be maintained and refurbished in orbit and may be returned to Earth for major refurbishment at 5-year intervals. The operational life of the system may be 15 years.

Discussions of the scientific potential and engineering challenges of a lunar surface telescope also began many years ago. To the astronomer, the Moon is an old friend. Kopal (1968) points out that Hipparchos knew the synodic month correctly to one second 22 centuries ago. In June 1780, William Hershel, as a young astronomer, wrote in a letter to the Astronomer Royal, "What a glorious View of the heavens from the Moon!" He went on to state that "For my part, were I to chuse between the Earth and the Moon, I should not hesitate a moment to fix upon the Moon for my habitation" (Kopal 1968).

Arthur C. Clarke in a 1954 book (Clarke and Smith) wrote that it is difficult to overestimate the value of the Moon as a site for astronomical observations. Earth telescopes transported to the Moon could be used at tenfold their efficiency on Earth. He acknowledged that special telescopes would be required for lunar conditions.

In 1964, a Lunar International Laboratory (LIL) panel anticipated a manned, permanent research center on the Moon. At the International Academy of Astronautics Lunar International Laboratory Project Symposium in Athem in 1965, it was noted (Malina 1969) that the Moon "represents... an ideal place to site an observatory for both optical and radio telescopes." Figures 1-3 illustrate concepts for lunar observatories suggested at the LIL Symposium (Malina 1969).

Herbig of Lick Observatory (North American Aviation, 1965a and 1965b) believed that the lunar telescope could be justified from a scientific point of view. Conferees at Falmouth (Astronomy Study Group 1965), Woods Hole (Working Group on Optical Astronomy 1966), and Santa Cruz (Astronomy Working Group 1967) investigated possibilities for lunar astronomical observatories.

NAS Space Science Board, 1965

Under the leadership of Harry H. Hess, Chairman, the Space Science Board of the National Academy of Sciences was convened at Woods Hole, Massachusetts, in 1965 to set directions for the future of space research. The Working Group on Optical Astronomy chaired by Lyman Spitzer met in June and July 1965 and recommended that in the time period 1965-1975, two or more 40-in aperture or larger telescopes be placed on the Moon as a part of the Apollo Extension Systems Program. They stated that the development of optical interferometers should be pressed with initial operation on Earth (Working Group on Optical Astronomy, 1966). They gave strong support

to a large diameter (120 in or more) orbiting telescope and emphasized the need for research and development of space telescope optics.

Research objectives of significance to the group at Woods Hole were listed:

1. Is the universe infinite or finite?
2. Is the universe steady state?
3. Are some physical laws still undiscovered?
4. Did all chemical elements build up from hydrogen?
5. How are stellar systems, stars, and planets formed?

They recognized that some key questions in astronomy would not be answered without space telescopes. Cited as such key questions were the cosmic distance scale, structures in galactic nuclei, molecular hydrogen distribution, and interstellar clouds radiating energy at about 100 microns.

The group at Woods Hole felt it was initially essential to test the ability of the astronaut to adjust, maintain, repair, and occasionally operate a large telescope in space.

NASA 1965 Summer Conference

In July 1965, the National Aeronautics and Space Administration conducted a Lunar Exploration and Science Conference in Falmouth, Massachusetts, under the leadership of Richard Allenby (Astronomy Study Group 1965). This conference followed the National Academy of Sciences Space Science Summer Study (Working Group on Optical Astronomy 1966) at Woods Hole, Massachusetts. At the Falmouth meeting, the special Astronomy Study Group convened by Nancy Roman of NASA had the following members: C. Fichtel, NASA Headquarters; K.G. Henize, Northwestern University; W. Markowitz, Naval Observatory; T.A. Mathews, California Institute of Technology; N.U. Mayall, Kitt Peak; John Naugle, NASA Headquarters; E.J. Ott, NASA Headquarters; E.E. Salpeter, Cornell University; and R.G. Stone, Goddard Space Flight Center, NASA.

Their recommended program was to encompass a 10-year period beginning with the first Apollo flights and considering scientific contributions by both manned and unmanned vehicles. The study was based on the likely capabilities of an Apollo Extension System (AES) which was to

make possible longer stay times, extended exploration capabilities, and support of lunar astronomy experiments (North American Aviation 1965b). This Astronomy Study Group made the following resolutions:

The group considered that the Moon offered an attractive and possibly unique base for astronomical observations and recommended evaluation of the lunar environment, including engineering properties and testing, with small telescopes on the Moon.

It was felt to be extremely important to start feasibility studies for a dish of approximately 100-f diameter to be used between millimeter and infrared wavelengths.

The group considered the information to be gained from radio astronomy observations at frequencies between 10MHz and 50kHz to be of considerable importance and recommended that a feasibility study should be started to determine whether the antenna should be placed in high Earth orbit or on the lunar surface, and the type of antenna to be used. Information about the lunar environment was needed to decide whether the Moon was a suitable place.

The major environmental areas requiring study were discussed for radio, optical and X- and gamma-ray astronomy and were listed as follows:

<u>Radio Astronomy</u>

1. Mechanical properties (bearing strength, stability, etc.)
2. Electrostatic charge (dust and surface rock)
3. Background noise (radio interference from Earth or spacecraft)
4. Impedance and dielectric properties (lunar subsurface)

<u>Optical Astronomy</u>

1. Mechanical properties (bearing strength, stability, etc.)
2. Micrometeroids (primary and secondary flux, erosion of mirrors, etc.)
3. Light background (luminescence, dust and atmosphere)
4. Thermal environment (above, on, and below the surface both lunar day and night)
5. Surface characteristics (reference points on Moon)

X- and Gamma-Ray Astronomy

1. X-ray background (from solar wind, cosmic ray, bombardment, etc.)
2. Gamma-ray background (radioactivity, etc.)

Adequate environmental data were not available in 1965, and the importance for all branches of astronomy of understanding the lunar environment was emphasized. It was concluded that the engineering and design of astronomical facilities on the Moon must proceed from an understanding of lunar environmental data.

NASA 1967 Summer Conference

At Santa Barbara, California, in 1967 the Astronomy Working Group had the following members: L.W. Fredrick, Chairman, University of Virginia; N.G. Roman, Cochairman, NASA Headquarters; R.C. Stokes, Secretary, NASA, Manned Spacecraft Center; S.L. Sharpless, University of Rochester; W.G. Tifft, University of Arizona; G.W. Simon, Sacramento Peak Observatory; W.R. Sheeley, Kitt Peak National Observatory; G.P. Garmire, California Institute of Technology; G.G. Fazio, Smithsonian Astrophysical Laboratories; R.G. Stone, NASA Goddard Space Flight Center; and S.J. Goldstein, University of Virginia.

The 1967 working group also defined a series of measurements to obtain data fundamental to the establishment of a lunar astronomical base. Measurements and instruments for making these measurements were listed and close cooperation between astronomers and other scientists in the final planning was recommended.

The four areas of astronomy considered were radio, X-ray and γ-ray, nonsolar optical, and solar optical astronomy. The report of this working group stated that radio astronomy, X-ray astronomy, and γ- ray astronomy require observations that probably can be made better on the lunar surface than in any other place. Optical astronomers were to decide the question of Earth-orbital versus lunar-based observations after obtaining more information on the lunar environment and comparisons with orbital experience.

The 1967 working group suggested that a single site may be suitable for all of the astronomical observations. They stated that X-ray and γ-ray occultation experiments require a

crater with a 50-km radius, the rim of which stands 1 km or more above a fairly flat crater floor. Radio astronomy requires an area of about 30 by 60 km. A site near the lunar equator was preferred. Optical astromoners preferred a site near the limb.

The following environmental characteristics of the lunar surface were listed for determination:

1. Micrometeorite environment.
2. Radiofrequency noise levels
3. Surface impedance and conductivity
4. Density and extent of the lunar ionosphere (if it exists)
5. X-ray and γ-ray intensities, including the zenith-angle distribution of the intensities.
6. Soil mechanics such as bearing strength and stability, depth profiles of temperature, seismic activity, and ionizing radiation
7. Thermal effects on astronomical instrumentation
8. Contaminants such as dust, spacecraft outgassing, spacecraft radiofrequency interference, and astronaut seismic noises
9. Deterioration of precision optical surfaces
10. Evaporation rates for optical coatings

It was noted that the Moon offers long-range advantages over Earth orbiting experiments. It is an extremely stable platform with a slow rotation rate which can be determined with high precision. A distant horizon can provide an excellent occulting edge for the determination of position and angular size of sources over a wide range of wavelengths to an accuracy probably unattainable with Earth orbiting instruments. Very long exposure times in combination with large area detectors can be used to achieve great sensitivity. Complex, large area experiments demanding relatively frequent servicing over long periods of time, can be best performed on the Moon.

Evaluation of the Moon as a site for a large telescope for optical astronomy with consideration given to environmental factors (that is, can large telescopes be operated on the Moon) and to scientific factors (that is, should large telescopes be operated on the Moon) is the central task for the early lunar astronomy program. The lunar investigation should begin with small site-testing packages and gradually incorporate more scientific packages to examine

operational and astronomical engineering problems and to demonstrate the extent to which the Moon offers unique advantages for optical astronomy.

According to the following excerpts from the 1967 Astronomy Working Group reports, the Moon may offer both scientific and environmental advantages over orbital systems:

1. The lunar night on or near the lunar far side offers the ultimate in minimizing background light and noise for faint-signal discrimination. In orbit, the primary light sources of the Sun, Earth, and Moon combine with complex time-dependent view patterns, scattering from structures, contaminants, and local radiation noise to degrade the ultimate signal-to-noise ratio obtainable.

2. The lunar horizon occults the Sun and thus permits near-solar access for measurements of the inner planets, comets, zodiacal light, and outer coronal features. Oribital systems become highly constrained within about 45° of the sunline.

3. The Moon provides a platform with a known time coordinate system which allows highly predictable and rapidly programmable orientation control, programmable drive, and single-star guidance control.

Other factors that offer advantages for specific problems include the following:

1. Access to virtually every point in the sky (in the dark) every lunar month for relatively long, uninterrupted periods

2. Availability of local radiation shielding so that film can be protected for long periods against cosmic rays

3. Minimal velocity-dependent effects such as differential aberration and Doppler shift during an observation

4. Low local magnetic fields

5. Flexibility of the manned interface

6. Long-term growth, self support, and operational flexibility

7. Location outside the geocorona of the Earth which will reduce the Lyman-α background brightness

The astronomical site suggested would be near but slightly south of the equatorial plane to provide favorable access to the Megallanic clouds which lie close to the south lunar rotational pole. If the southern latitude is too great, an appreciable segment of the sky will be lost in the north circumpolar cap. A desirable latitude range appears to be -5° to ±3°.

The site for the very large telescope should be on the far side of the Moon, continuously beyond the visible range of the Earth, to achieve the best dark conditions through the elimination of earthlight. There is no optical requirement that the site be more than slightly beyond the maximum libration limb, and a site which libration occasionally brings into view of the Earth is acceptable. Since the ultimate desirability of farside operations may present an initial operational restriction, early exploration may be desirable for a second near-side limb site with a longitude from the central meridian of 75° ±10°.

The two near-side limb sites lie near Grimaldi and Langrenus. Both areas have moderately broken terrain. The terrain at the final site should be fairly flat without great local roughness or an irregular horizon. The southern horizon, particularly, should be unobstructed. A slight elevation favoring southern exposure and perhaps somewhat above the lowest levels of the possible secondary ejecta haze should be considered. The highest site altitude that can be achieved without recourse to very rugged terrain may be advantageous.

The Large Optical Observatory

In a 1965 study for NASA (North American Aviation 1965a), G.H. Herbig of Lick Observatory listed four conditions that an optical telescope on the Moon should satisfy:

1. The telescope must operate effectively in the 1000 to 1500Å region (as well as at longer wave lengths). An aperture of at least 100 in was specified for a diffraction-limited telescope to operate effectively in this region.

2. Astronomers using the instrument should be adequately shielded and able to work using fixed receiver operable without the encumbrance offered by spacesuits.

3. The most valuable optics must be protected against possible damage and misalignments owing to temperature changes and particle impact.

4. The design of the telescope systems should take into account the nature of the lunar environment, the high cost of transporting massive movable structures to the Moon, and the relatively high cost of construction and operation manhours expended on the Moon.

Herbig suggested that a fixed horizontal telescope with the following components could be established on the Moon:

1. A reflector in a fixed position in a tunnel and not exposed directly to the lunar sky.

2. A single moving flat mirror exposed to the outside. This mirror would be driven by a servomechanism programmed for observations from the Moon. Radiation incident on this mirror would be reflected through a tunnel to the reflector.

3. A grating spectrograph mounted at a focus of the telescope and operable from a environment in which astronomers could work without pressurized suits.

4. A pressurized and well-equipped laboratory having access to a large-scale focus. Here would be the instruments required for investigating star images formed in the focal plane.

A possible configuration of the horizontal telescope is shown in figure 4. The estimated Earth weight delivered to the surface of the Moon (North American Aviation 1966b) would have been 18,000 k (39,600 lb). A vertical telescope was subsequently considered requiring mounting the 200-in flat mirror directly above rather than to the side of the 100-in reflector.

The 100-in telescope would have required an advanced space transportation system to reduce the costs of lunar payload delivery. The telescope would have been part of a previously established manned lunar base that housed construction engineers and furnished power and other support to the observatory during and after construction and checkout. This discussion stated that

a lunar observatory of this configuration might be 15 to 20 years in the future but it was a worthy goal.

A Lockheed (1967) MIMOSA Program to commence in 1971 and extend until 1988 involved 1-m optical telescopes set up at the south pole and the center of the farside to evaluate the potential of lunar-based astronomy. A 12-man permanent base in the crater Grimaldi was to use an array of radio, optical, and X ray telescopes. MIMOSA was based on an upgraded Saturn V launch rate of three to four per year through the 1970s and six per year in the 1980s.

Hynek and Powers (1970) proposed a design for a small photometer to be used for observatory site surveys on the Moon. Their goal was to monitor background brightness in the range of wavelengths from Lyman-α to the visual and scattered light as a function of elevation and deterioration of optics. They valued the Moon as a site because of its predictable motions, its capacity to absorb heat as well as angular momentum, the Moon's slow rate of rotation, and the location away from Van Allen belts and Earth-centered debris in space. They argued for a 25.4-cm telescope to be placed on the Moon to do a galaxy count in the near infrared.

Constructing an Observatory on the Moon

Johnson et al. (1971) used Surveyor and Apollo mission soil mechanics and other results in an investigation of the lunar regolith as a site for an astronomical observatory. A telescope system was postulated involving a large reflector, and foundations were designed for cases of a deep regolith and a shallow regolith. It was noted that the lunar soil is fine-grained, relatively dense, and weakly cohesive and will support anticipated observatory loads with proper design of foundation components. More information is needed on the behavior of the surface under repeated and dynamic loads.

There are known to be significant variations in the lunar soil both laterally and with depth as revealed by trenching and core tubes (Johnson and Carrier 1971; Carrier et al.1972). In emplacing an observatory on the Moon, it will be necessary to have knowledge of soil and rock profiles and engineering properties at depth and to monitor soil and foundation behavior during observatory placement. It may be feasible to compact or stabilize the regolity. The wide range in lunar temperatures implies a thermal cycling (and expansion and contraction) of the regolith, suggesting that foundations should be placed below the depth of thermal cycling. Both total and differential settlements are to be controlled appropriately.

Previously, Johnson (1964) considered criteria for lunar base structures, taking into account gravitational, vacuum, and other effects. Since the 1960s, a variety of new materials and control technologies have been developed that offer promise for a use in design of a lunar observatory. The materials include graphite epoxy and metal matrix composites with low coefficients of thermal expansion and high strength and stiffness. The controls technologies are consistent with progress in adaptive optics. Early facilities will probably be fabricated on Earth but later facilities may be partly constructed with materials made from lunar resources. Sensitive components will be shielded by burial in the lunar regolith. Air-inflated structures offer the possibility of providing mobile repair hangars that could be used at remote observatory sites.

When robots and automated construction equipment are used on the Moon, consideration will have to be given to a myriad of design details. For example, connections and hookups (e.g., for fluids) must take a positive connection with little adjustment required. Semiautonomous construction equipment offers the possibility of providing tremendous cost savings in building and maintaining a lunar observatory. Developments on Earth are already validating concepts of semiautonomous telecommanded systems of construction and exploratory vehicles and equipment for use in hazardous environments and in military contexts.

Recent Proposals

There have been two conferences on Lunar Bases and Space Activities in the 21st Century, and at both conferences (in 1984 and 1988) the possibilities of lunar observatories have been discussed. The idea of a lunar optical/infrared synthesis array was presented by Burke (1984) at the 1984 conference.

At a January 1986 meeting in Houston, Texas, attended by about 100 astronomers, space scientists, physicists, and engineers, the challenge was to consider astronomical observations from a lunar base. Burns (Burns and Mendell 1988) noted there was a remarkable consensus from this group that the Moon is very likely the best location in the inner solar system to site an observatory for cutting-edge research in astronomy.

In August 1988, at a conference on Engineering, Construction, and Operations in Space, five papers relating to lunar observatories were presented and three of these were published in the proceedings (Johnson and Wetzel 1988). These papers described modest astronomy facilities for

an early lunar base and, later, more elaborate facilities (Burns 1988b; Zeilik 1988) as well as needed advanced technologies (Johnson and Wetzel 1988) such as light-weight steerable parabolic antennae (Akgul, Gertsle, and Johnson 1988). Also considered were transient atmospheres resulting from human activities on the Moon and the persistence and possible detrimental effects of these gas clouds on the effectiveness of lunar astronomical observatories (Fernini et al. 1988).

The Office of Exploration 1988 Annual Report to the NASA Administrator identified three pathways for human exploration of the Moon and Mars. Each begins from Space Station Freedom and for each pathway, candidate missions were identified as case studies. One of the four candidates is a lunar observatory. The lunar observatory case study has as its objective an understanding of the effort to construct and operate a human-tended farside lunar observatory with optical arrays, stellar monitoring capability, and radio telescopes (Office of Exploration 1988a and 1988b).

Summary and Conclusions

Suggestions for astronomical observatories in space date back at least to Herman Oberth in 1923. The desirability of telescopes on the Moon was apparently alluded to by Hershel in 1790. A more specific rationale was stated in 1954 by Arthur C. Clarke. Malina and coworkers offered design concepts for telescopes on the Moon in the 1960s. Several different working groups convened in the 1960s developed ideas for observatories on the Moon and listed information needed on the lunar environment to facilitate engineerng designs. The importance of the optical interferometer was recognized (circa 1965) in these working group discussions. Several aerospace companies were engaged by NASA to develop design concepts for lunar observatories in the 1960s.

In the 1980s and 1990s, the technologies for lunar observatories encompass light-weight thin mirrors, adaptive optics, controls, robotics, fiber-reinforced composite materials, advanced sensors, and improved data storage and processing and transmission capabilities. The dreams of the 50s and 60s for lunar observatories are becoming more readily achievable. Results from Apollo lunar missions are available. What remains to be done is to mount a steady effort to establish an optical telescope on the Moon. A step-by-step effort can achieve the goal of a significant functioning optical interferometer on the Moon in the 21st Century.

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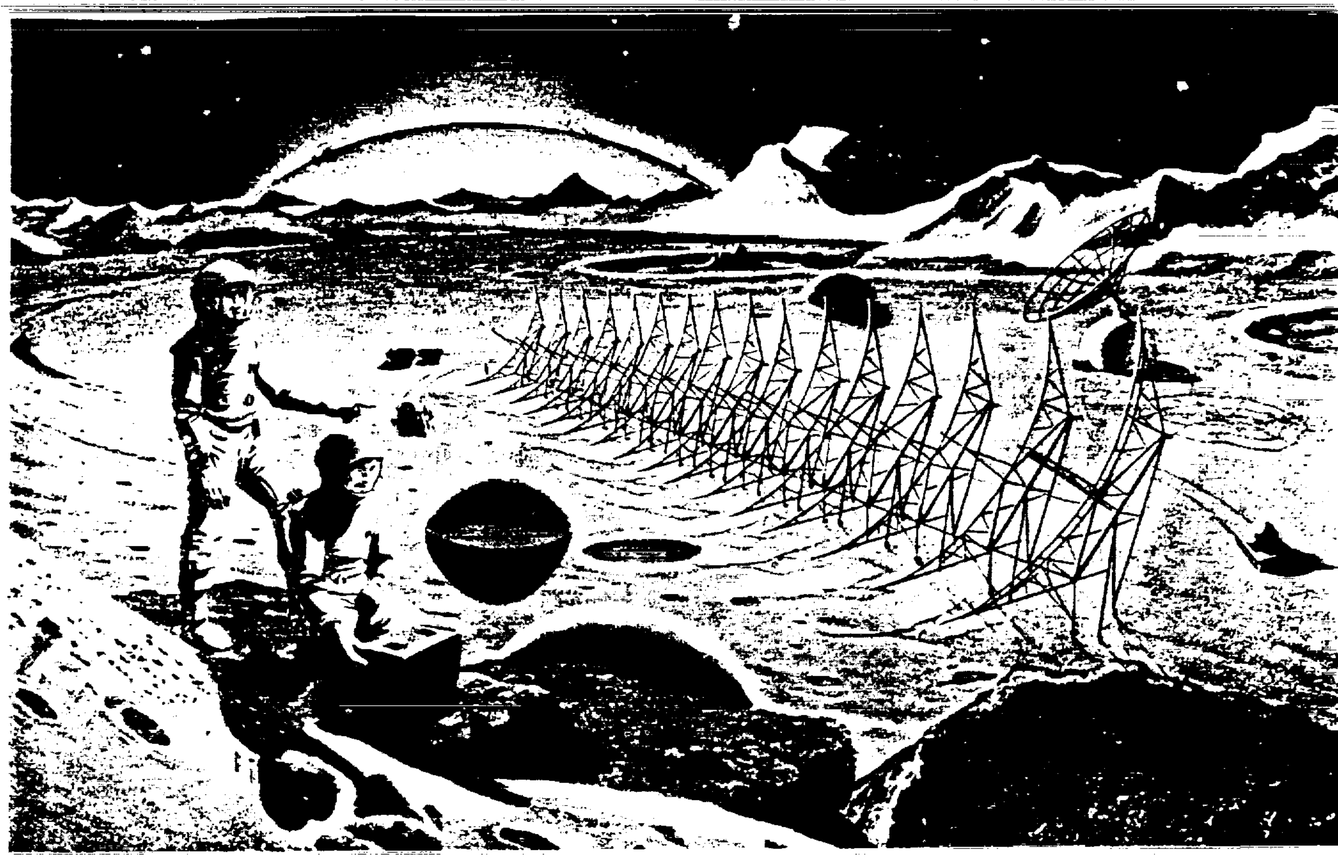

Figure 1: Radio astronomy from the Moon has three advantages over terrestrial observation: man-made, terrestrial-originating background noise is avoided (particularly on the far side); there is less gravitational pull to cause distortions in the structures; and there is a slower period of rotation relative to objects being observed (from Malina 1969).

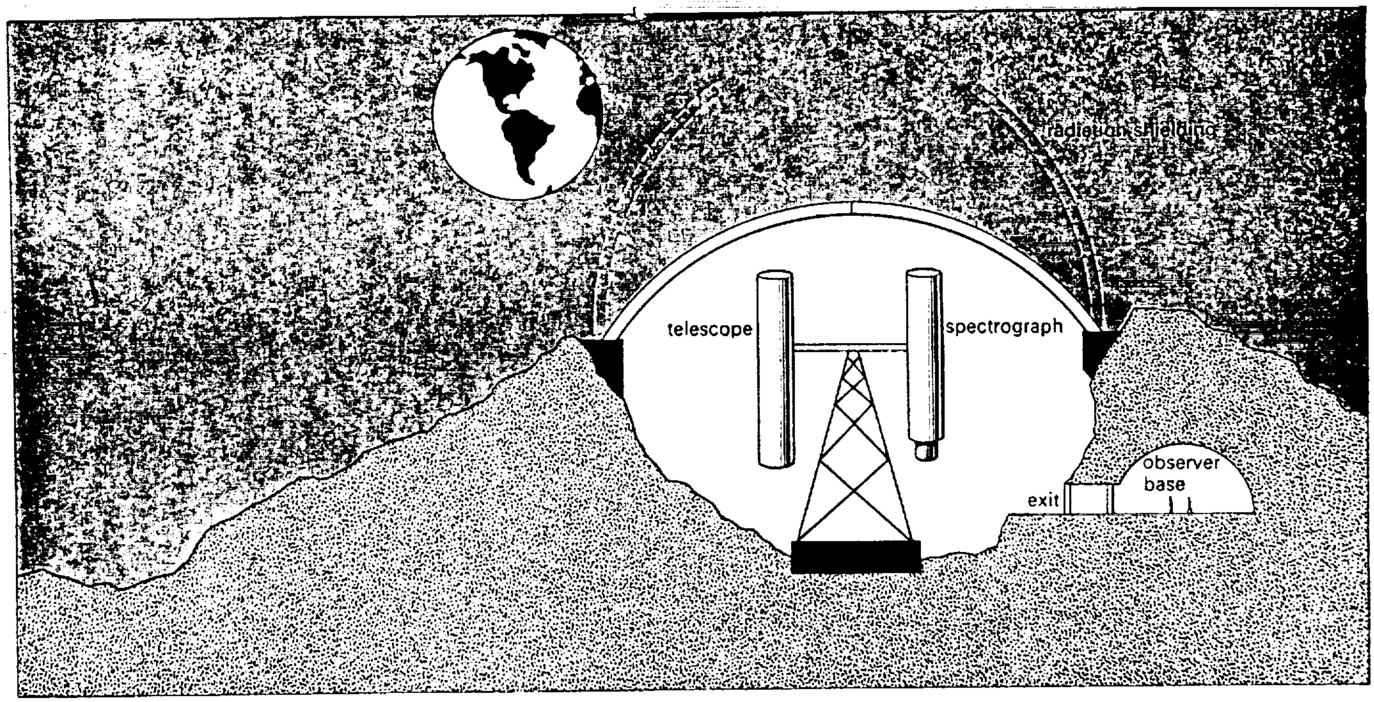

Figure 2: The Lunar International Symposium (LIL) of 1965 suggested this semi-permanent observatory in a small lunar crater. Radiation shielding lids of expanded foam materials are shown (Malina 1969).

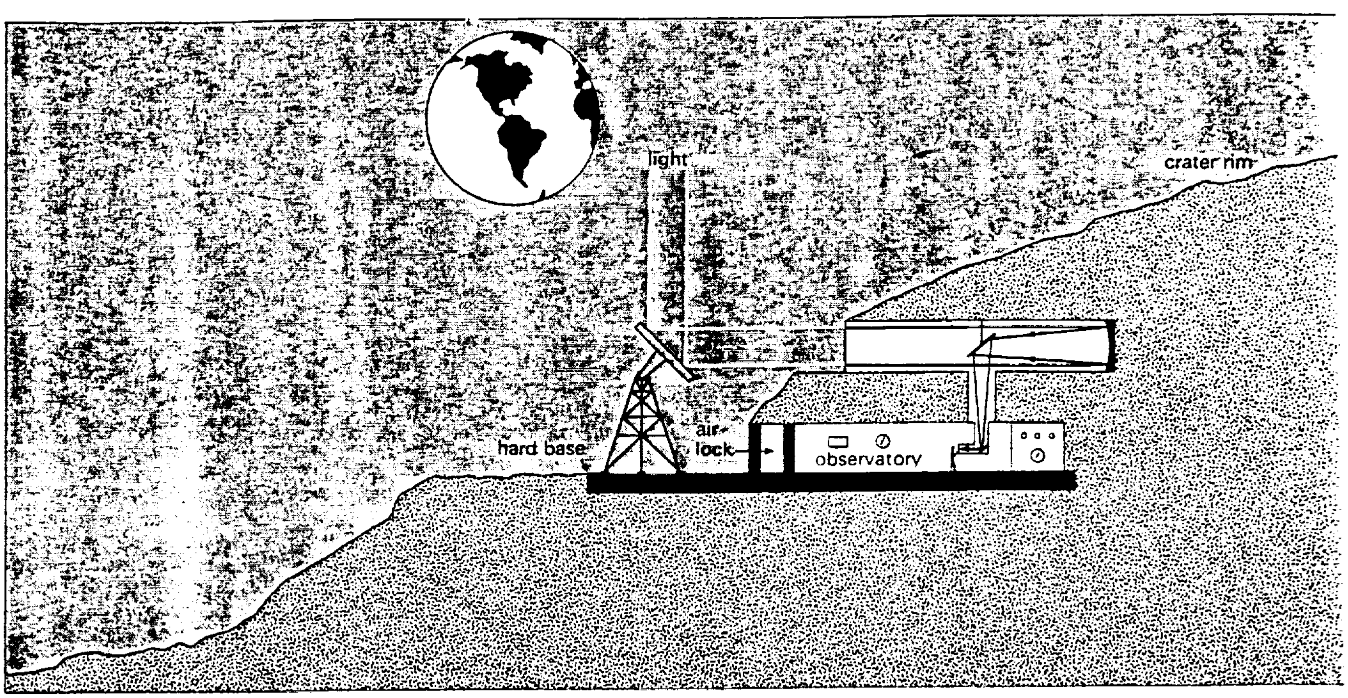

Figure 3: This fixed-based observatory was also proposed at LIL such that sensitive equipment could be protected by a considerable thickness of lunar soil and rock (Malina 1969).

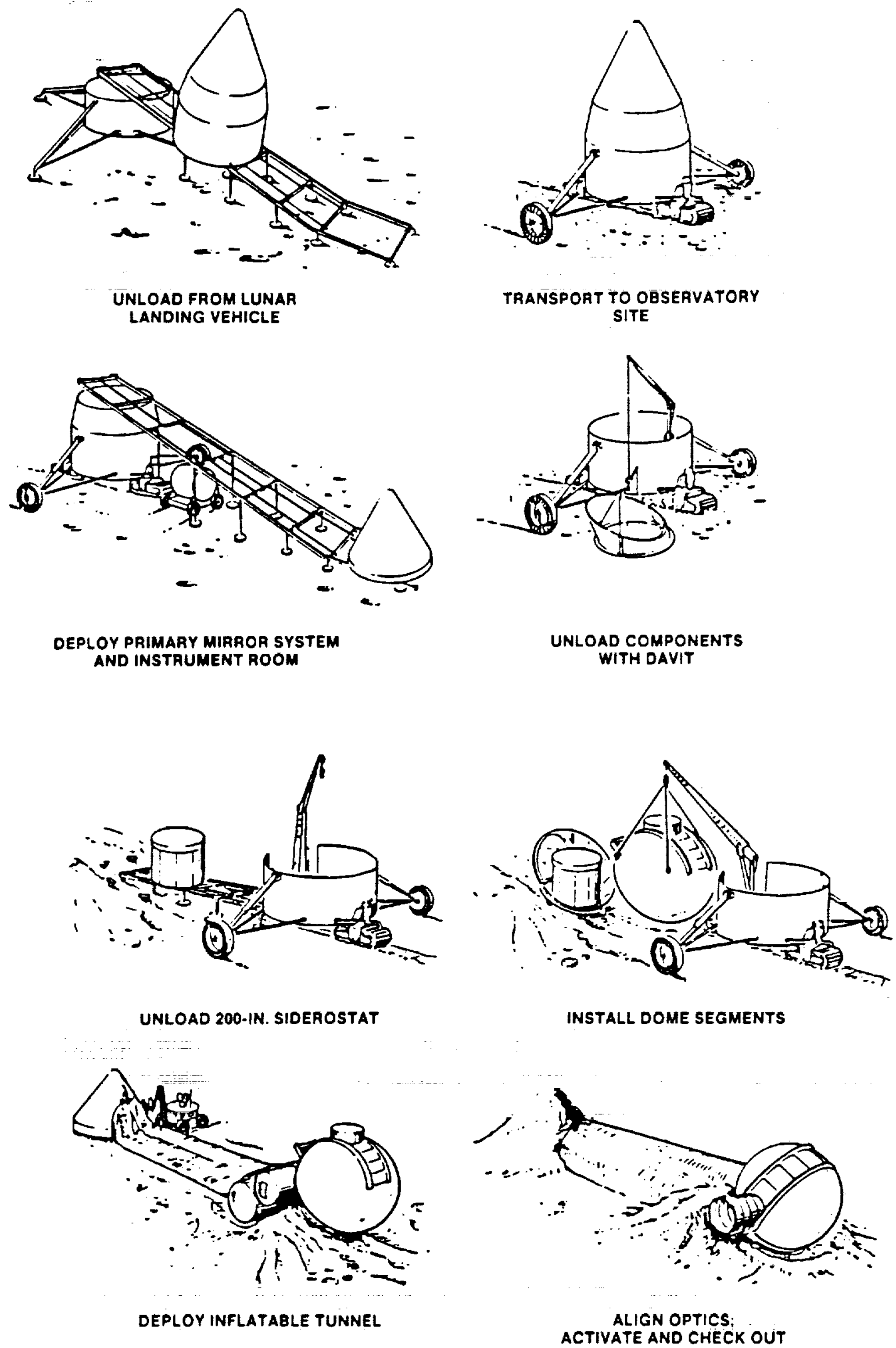

Figure 4: Deployment of 100-in. horizontal telescope.